SLAC-PUB-8335
January 2000

Z' Bosons and Kaluza-Klein Excitations at Muon Colliders [1]

Thomas G Rizzo [2]

Stanford Linear Accelerator Center
Stanford CA 94309, USA

Abstract. After an extremely brief overview of the discovery reach for Z' bosons, we will discuss the physics of Kaluza-Klein(KK) excitations of the Standard Model gauge bosons that can be explored by a high energy muon collider in the era after the LHC and TeV Linear Collider. We demonstrate that the muon collider is a necessary ingredient in the unraveling the properties of such KK states and, perhaps, proving their existence.

SEARCH REACHES FOR Z' BOSONS

The indirect search reach for new gauge bosons at future colliders has been the subject of much investigation but with few new results in the past couple of years except for refinements of previously existing analyses. We refer the reader to the summaries provided in Ref. [1].

KK EXCITATIONS OF SM GAUGE BOSONS

In theories with extra dimensions, $d \geq 1$, the gauge fields of the Standard Model(SM) will have Kaluza-Klein(KK) excitations if they are allowed to propagate in the bulk of the extra dimensions. If such a scenario is realized then, level

---

[1] To appear in the *Proceedings of the* 5^{th} *International Conference on Physics Potential and Development of* $\mu^+\mu^-$ *Colliders*, Fairmont Hotel, San Francisco, CA, 15-17 December 1999

[2] E-mail:rizzo@slacvx.slac.stanford.edu. Work supported by the Department of Energy, Contract DE-AC03-76SF00515

by level, the masses of the excited states of the photon, Z, W and gluon would form highly degenerate towers. The possibility that the masses of the lowest lying of these states could be as low as $\sim$ a few TeV or less leads to a very rich and exciting phenomenology at future and, possibly, existing colliders [2]. For the case of one extra dimension compactified on S^1/Z_2 the spectrum of the excited states is given by $M_n = n/R$ and the couplings of the excited modes relative to the corresponding zero mode to states remaining on the wall at the orbifold fixed points, such as the SM fermions, is simply $\sqrt{2}$ for all n.

If such KK states exist what is the lower bound on their mass? We already know from direct Z'/W' and dijet bump searches at the Tevatron from Run I that they must lie above $\simeq 0.85$ TeV. A null result for a search made with data from Run II will push this limit to $\simeq 1.1$ TeV. To do better than this at present we must rely on the indirect effects associated with KK tower exchange. Such limits rely upon a number of additional assumptions, in particular, that the effect of KK exchanges is the *only* new physics beyond the SM. The strongest and least model-dependent of these bounds arises from an analysis of charged current contact interactions at both HERA and the Tevatron [3] where one obtains a bound of $R^{-1} > 3.4$ TeV. Similar analyses have been carried out by a number of authors [4,5]; the best limit arises from an updated combined fit to the precision electroweak data as presented at the 1999 summer conferences and yields [6] $R^{-1} > 3.9$ TeV for the case of one extra dimension. From the previous discussion we can also draw a further conclusion for the case $d = 1$: the lower bound $M_1 > 3.9$ TeV is so strong that the *second* KK excitations, whose masses must now exceed 7.8 TeV due to the above scaling law, will be beyond the reach of the LHC and thus the LHC will *at most* only detect the first set of KK excitations for $d = 1$.

In all analyses that obtain indirect limits on M_1, one is actually constraining a dimensionless quantity such as

$$V = \sum_{\mathbf{n}=1}^{\infty} \frac{g_{\mathbf{n}}^2}{g_0^2} \frac{M_w^2}{M_{\mathbf{n}}^2}\,, \tag{1}$$

where, generalizing the case to d additional dimensions, $g_{\mathbf{n}}$ is the coupling and $M_{\mathbf{n}}$ the mass of the n^{th} KK level labelled by the set of d integers $\mathbf{n}$ and M_w is the W boson mass which we employ as a typical weak scale factor. For $d = 1$ this sum is finite since $M_n = n/R$ and $g_n/g_0 = \sqrt{2}$ for $n > 1$; one immediately obtains $V = \frac{\pi^2}{3}(M_w/M_1)^2$ with M_1 being the mass of the first KK excitation. From the precision data one obtains a bound on V and then uses the above expression to obtain the corresponding bound on M_1. For $d > 1$, however, independently of how the extra dimensions are compactified, the above sum in V *diverges* and so it is not so straightforward to obtain a bound on M_1. We also recall that for $d > 1$ the mass spectrum and the relative coupling strength of any particular KK excitation now become dependent upon how the additional dimensions are compactified.

There are several ways one can deal with this divergence: (i) The simplest approach is to argue that as the states being summed in V get heavier they approach

the mass of the string scale, M_s, above which we know little and some new theory presumably takes over. Thus we should just truncate the sum at some fixed maximum value $n_{max} \simeq M_s R$ so that masses KK masses above M_s do not contribute. (*ii*) A second possibility is to note that the wall on which the SM fermions reside is not completely rigid having a finite tension. The authors in Ref. [7] argue that this wall tension can act like an exponential suppression of the couplings of the higher KK states in the tower thus rendering the summation finite, *i.e.*, $g_{\mathbf{n}}^2 \to g_{\mathbf{n}}^2 e^{-(M_n/M_1)^2/n_{max}^2}$, where n_{max} now parameterizes the strength of the exponential cut-off. Antoniadis [6] has argued that such an gaussian suppression can also arise from considerations of string scattering amplitudes at high energies. (*iii*) A last scenario [8] is to note the possibility that the SM wall fermions may have a finite size in the extra dimensions which smear out and soften the couplings appearing in the sum to yield a finite result. In this case the suppression is also of the Gaussian variety. Table I shows how the $d = 1$ lower bound of 3.9 TeV for the mass of M_1 changes as we consider different compactifications for $d > 1$. We see that in some cases the value of M_1 is so large it will be beyond the mass range accessible to the LHC as it is for all cases of the $d = 3$ example.

TABLE 1. Lower bound on the mass of the first KK state in TeV resulting from the constraint on V for the case of more than one dimension. 'T'['E'] labels the result obtained from the direct truncation (exponential suppression). Cases labeled by an asterisk will be observable at the LHC. $Z_2 \times Z_2$ and $Z_{3,6}$ correspond to compactifications in the case of $d = 2$ while $Z_2 \times Z_2 \times Z_2$ is for the case of $d = 3$.

	$Z_2 \times Z_2$		$Z_{3,6}$		$Z_2 \times Z_2 \times Z_2$	
n_{max}	T	E	T	E	T	E
2	5.69*	4.23*	6.63*	4.77*	8.65	8.01
3	6.64	4.87*	7.41	5.43*	11.7	10.8
4	7.20	5.28*	7.95	5.85*	13.7	13.0
5	7.69	5.58*	8.36	6.17*	15.7	14.9
10	8.89	6.42	9.61	7.05	23.2	22.0
20	9.95	7.16	10.2	7.83	33.5	31.8
50	11.2	8.04	12.1	8.75	53.5	50.9

SM KK STATES BEFORE THE MUON COLLIDER

Let us return to the $d = 1$ case at the LHC where the degenerate KK states $\gamma^{(1)}$, $Z^{(1)}$, $W^{(1)}$ and $g^{(1)}$ are potentially visible. It has been shown [6] that for masses in excess of $\simeq 4$ TeV the $g^{(1)}$ resonance in dijets will be washed out due

to its rather large width and the experimental jet energy resolution available at the LHC detectors. Furthermore, $\gamma^{(1)}$ and $Z^{(1)}$ will appear as a *single* resonance in Drell-Yan that cannot be resolved and looking very much like a single Z' as can be seen in Fig.1. Thus if we are lucky the LHC will observe what appears to be a degenerate Z'/W'. How can we identify these states as KK excitations when we remember that the rest of the members of the tower are too massive to be produced? We remind the reader that many extended electroweak models exist which predict a degenerate Z'/W'. Without further information, it would seem likely that this would become the most likely guess of what had been found. In the case of the 4 TeV resonance there is sufficient statistics that the KK mass will be well measured and one can also imagine measuring the forward-backward asymmetry, A_{FB}, if not the full angular distribution of the outgoing leptons, since the final state muon charges can be signed. However, for such a heavy resonance it is unlikely that much further information could be obtained about its couplings and other properties based on the conclusion of several years of Z' analyses. Thus we will never know from LHC data alone whether the first KK resonance has been discovered or, instead, some extended gauge model scenario has been realized. To make further progress we need a lepton collider.

It is well-known that future e^+e^- linear colliders(LC) operating in the center of mass energy range $\sqrt{s} = 0.5 - 1.5$ TeV will be sensitive to indirect effects arising from the exchange of new Z' bosons with masses typically 6-7 times greater than $\sqrt{s}$ [1]. This sensitivity is even greater in the case of KK excitations since towers of both γ and Z exist all of which have couplings larger than their SM zero modes. Furthermore, analyses have shown that with enough statistics the couplings of the new Z' to the SM fermions can be extracted [1] in a rather precise manner, especially when the Z' mass is already approximately known from elsewhere, *e.g.*, the LHC. In the present situation, we imagine that the LHC has discovered and determined the mass of a Z'-like resonance in the 4-6 TeV range. Can the LC tell us anything about the couplings of this object?

We find that it is sufficient for our arguments below to do this solely for the leptonic channels. The idea is the following: we measure the deviations in the differential cross sections and angular dependent Left-Right polarization asymmetry, A_{LR}^{ℓ}, for the three lepton generations and combine those with τ polarization data. Assuming lepton universality(which would be observed in the LHC data anyway), that the resonance mass is well determined, and that the resonance is an ordinary Z' we perform a fit to the hypothetical Z' coupling to leptons. To be specific, let us consider the case of only one extra dimension with a 4 TeV KK excitation and employ a $\sqrt{s} = 500$ GeV collider with an integrated luminosity of 200 fb^{-1}. The result of performing this fit demonstrate, as shown in Ref. [9], that the coupling values are 'well determined', *i.e.*, the size of the 95% CL allowed region we find is quite small as we would have expected from previous Z' analyses.

The only problem with the fit is that the χ^2 is very large leading to a very small

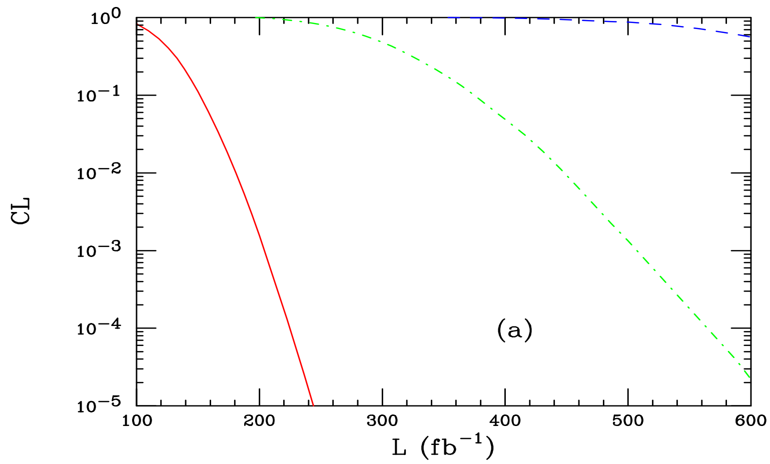

FIGURE 1. CL as a function of the integrated luminosity resulting from the coupling fits following from the analysis discussed in the text for both a 500 GeV e^+e^- collider. In the solid(dash-dotted,dotted) curve corresponds to a first KK excitation mass of 4(5,6) TeV.

confidence level, *i.e.*, $\chi^2/d.o.f. = 95.06/58$ or CL=1.55×10^{-3}! For an ordinary Z' it has been shown that fits of much higher quality, based on confidence level values, are obtained by this same procedure. Fig.2 shows the results for the CL following the above approach as we vary both the luminosity and the mass of the first KK excitation at a 500 GeV e^+e^- linear collider. From this analysis one finds that the resulting CL is below $\simeq 10^{-3}$ for a first KK excitation with a mass of 4(5,6) TeV when the integrated luminosity at the 500 GeV collider is 200(500,900)fb^{-1} whereas at a 1 TeV for excitation masses of 5(6,7) TeV we require luminosities of 150(300,500)fb^{-1} to realize this same CL. Barring some unknown systematic effect the only conclusion that one could draw from such bad fits is that the hypothesis of a single Z', and the existence of no other new physics, is simply *wrong*. If no other exotic states are observed below the first KK mass at the LHC, this result would give very strong indirect evidence that something more unusual than a conventional Z' had been found but it *cannot* prove that this is a KK state.

SM KK STATES AT MUON COLLIDERS

In order to be completely sure of the nature of the first KK excitation, we must produce it directly at a higher energy lepton collider and sit on and near the peak of the KK resonance. To reach this mass range will most likely require a Muon Collider. Sitting on the resonance there are a very large number of quantities that can be measured: the mass and apparent total width, the peak cross section, various partial widths and asymmetries *etc*. From the Z-pole studies at SLC and LEP, we recall a few important tree-level results which we would expect to apply here as well provided our resonance is a simple Z'. First, we know that the value

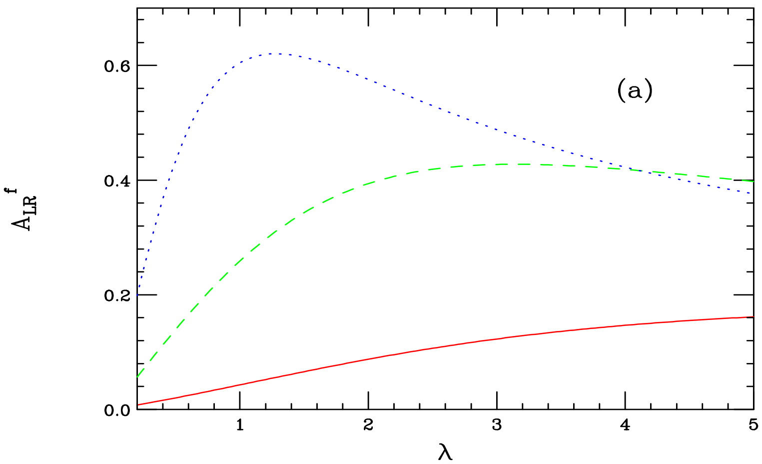

FIGURE 2. A^f_{LR} as a function of the parameter λ for $f = \ell$(solid), $f = c$(dashed) and $f = b$(dots).

of A_{LR}, as measured on the Z by SLD, does not depend on the fermion flavor of the final state and second, that the relationship $A_{LR} \cdot A^{pol}_{FB}(f) = A^f_{FB}$ holds, where $A^{pol}_{FB}(f)$ is the polarized Forward-Backward asymmetry as measured for the Z at SLC and A^f_{FB} is the usual Forward-Backward asymmetry. The above relation is seen to be trivially satisfied on the Z(or on a Z') since $A^{pol}_{FB}(f) = \frac{3}{4}A_f$, $A_{LR} = A_e$, and $A^f_{FB} = \frac{3}{4}A_e A_f$. Both of these relations are easily shown to fail in the present case of a 'dual' resonance though they will hold if only one particle is resonating.

A short exercise [6] yields the results in Fig.2 explicitly showing the flavor dependence of A_{LR}. In principle, to be as model independent as possible in a numerical analysis, we should allow the individual widths Γ_i of the two resonances to be greater than or equal to their SM values as such heavy KK states may decay to SM SUSY partners as well as to presently unknown exotic states. Since the expressions above only depend upon the ratio of widths, we let $R = \lambda R_0$ where R_0 is the width ratio obtained assuming that the KK states have only SM decay modes. We then treat λ as a free parameter in what follows and explore the range $1/5 \leq \lambda \leq 5$. Once λ is determined from the value of one observable all of the electroweak parameters of the dual resonance are completely fixed and can directly compared with data proving that a composite resonance corresponding to the first KK excitation has been discovered [9].

In Figs. 3a and 3b we show that although on-resonance measurements of the electroweak observables, being quadratic in the $Z^{(1)}$ and $\gamma^{(1)}$ couplings, will not distinguish between the usual KK scenario and that of the Arkani-Hamed and Schmaltz(AS) (whose KK couplings to quarks are of opposite sign from the conventional assignments for odd KK levels since quarks and leptons are assumed to be separated by a distance $D = \pi R$ in their scenario) the data below the peak in the

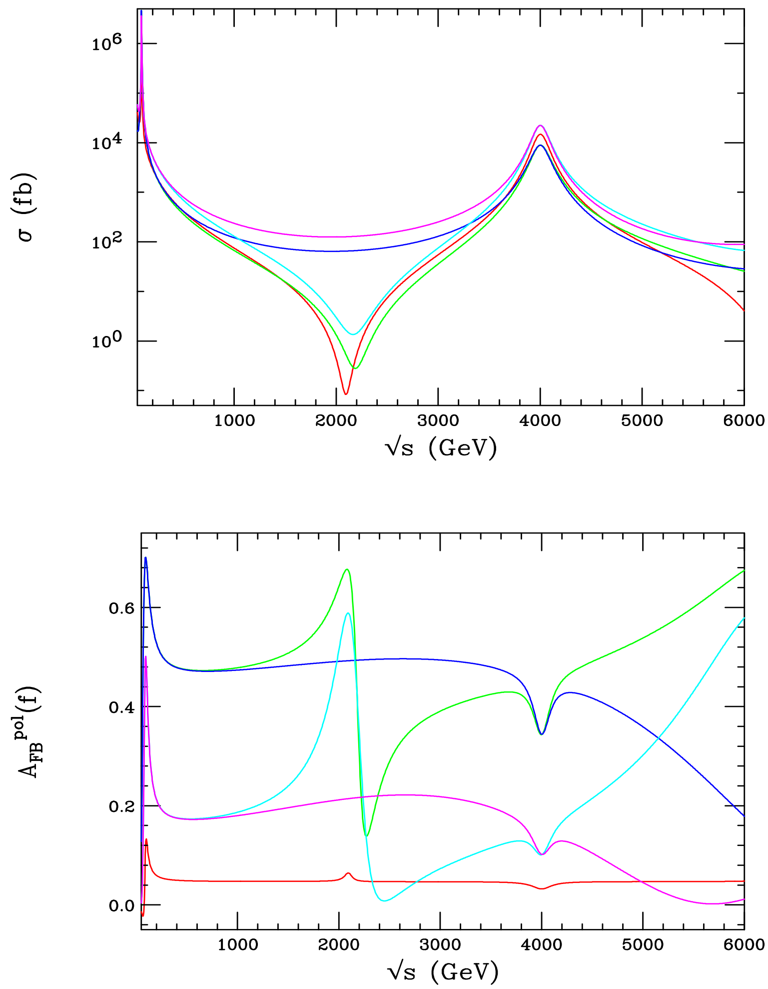

FIGURE 3. Cross sections and polarized A_{FB} for $\mu^+\mu^- \to e^+e^-$ $b\bar{b}$ and $c\bar{c}$ as functions of energy in both the 'conventional' scenario and that of Arkani-Hamed and Schmaltz(AS) [8] where the quarks and leptons are separated in the extra dimension by a distance $D = \pi R$. The red curve applies for the μ final state in either model whereas the green(blue) and cyan(magenta) curves label the b and c final states for the 'conventional'(AS) scenario.

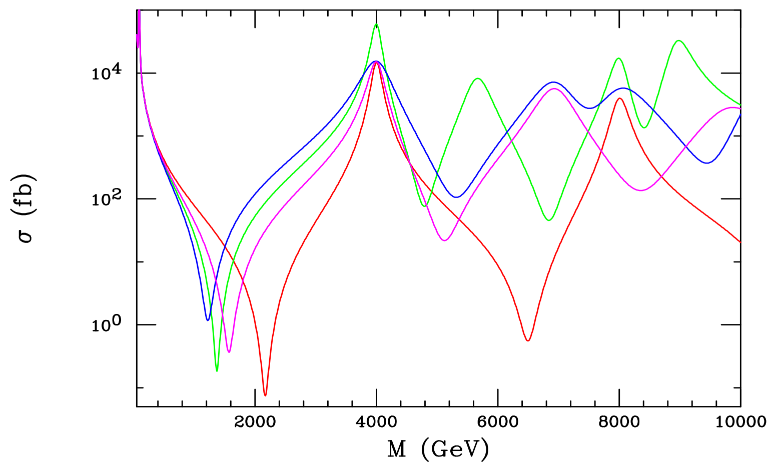

FIGURE 4. Same as Fig. 3a for the process $\mu^+\mu^- \to e^+e^-$ but now also including the models listed in Table 1 with $d = 2$ assuming $M_1 = 4$ TeV. The red(green,blue,purple) curve corresponds to the $S^1/Z_2(Z_2 \times Z_2,\ Z_{3,6},\ S^2)$ compactifications.

hadronic channel will easily allow such a separation. The cross section and asymmetries for $\mu^+\mu^- \to e^+e^-$ is, of course, the same in both cases. Such data can be collected by using radiative returns if sufficient luminosity is available. The combination of on and near resonance measurements will thus completely determine the nature of the resonance as well as the separation between various fermions on the wall. Fig.4 shows that with even larger energies muon colliders will be able to probe both the number of extra dimensions as well as the geometry of their compactification manifolds since these can be uniquely determined by the KK excitation spectrum.

REFERENCES

1. For a review, see T.G. Rizzo in *New Directions for High Energy Physics: Snowmass 1996*, ed. D.G. Cassel, L. Trindle Gennari and R.H. Siemann, (SLAC, 1997), hep-ph/9612440; A. Leike, Phys. Rep. **317**, 143 (1999).
2. I. Antoniadis, Phys. Lett. **B246**, 377 (1990); I. Antoniadis, C. Munoz and M. Quiros, Nucl. Phys. **B397**, 515 (1993); I. Antoniadis and K. Benalki, Phys. Lett. **B326**, 69 (1994); I. Antoniadis, K. Benalki and M. Quiros, Phys. Lett. **B331**, 313 (1994).
3. F. Cornet, M. Relano and J. Rico, hep-ph/9908299.
4. P. Nath and M. Yamaguchi, hep-ph/9902323 and hep-ph/9903298; M. Masip and A. Pomarol, hep-ph/9902467; W.J. Marciano, hep-ph/9903451; L. Hall and C. Kolda, Phys. Lett. **B459**, 213 (1999); R. Casalbuoni, S. DeCurtis and D. Dominici, hep-ph/9905568; R. Casalbuoni, S. DeCurtis, D. Dominici and R. Gatto, hep-ph/9907355; A. Strumia, hep-ph/9906266; C.D. Carone, hep-ph/9907362.
5. T.G. Rizzo and J.D. Wells, hep-ph/9906234.
6. T.G. Rizzo, hep-ph/9909232; See also I. Antoniadis, K. Benalki and M. Quiros, hep-ph/9905311; P. Nath, Y. Yamada and M. Yamaguchi, hep-ph/9905415.

7. M. Bando, T. Kugo, T. Noguchi and K. Yoshioka, hep-ph/9906549. See also J. Hisano and N. Okada, hep-ph/9909555.
8. N. Arkani-Hamed and M. Schmaltz, hep-ph/9903417; N. Arkani-Hamed, Y. Grossman and M. Schmaltz, hep-ph/9909411.
9. For details, see the first paper in Ref. [6].